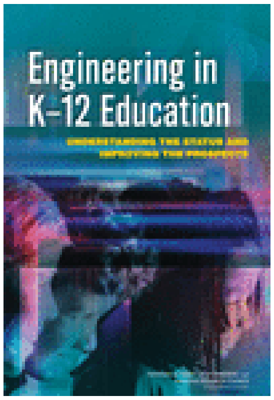

Engineering in K-12 Education: Understanding the Status and Improving the Prospects

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Teaching and Learning Core Engineering Concepts and Skills in Grades K–12

Curriculum initiatives in the K–12 setting that include engineering content and courses (primarily in the context of science) have raised questions about teaching engineering to pre-college students, and especially pre-high school students. In response to these concerns, studies have been undertaken on a number of issues, including determining whether K–12 students, who have limited knowledge of basic mathematical concepts, can learn engineering concepts and skills and whether "positioning engineering design primarily as a tool for science learning runs the risk of misrepresenting . . . engineering as *applied science*" (Leonard, 2004).

Although engineering is rarely taught explicitly in K–12 classrooms in the United States, a growing body of evidence on the teaching and learning of core engineering concepts and skills suggests that elementary students are capable of engaging with this material. The committee commissioned two reviews (Silk and Schunn [2008] and Petrosino, Svihla, and Brophy [2008]) of this growing body of evidence. The relative paucity of research on K–12 students' understanding of engineering concepts and skills places significant limitations on what can be currently claimed. The following review presents our current best understanding of learning trends in this domain, including the challenges inherent in designing engineering instruction for K–12 students.

Deciding on the scope and sequence of teaching engineering-related concepts and skills can be difficult, sometimes even controversial. Like

scientists, engineers in different areas of engineering require different sets of specific skills and concepts. The reviewers focused on core concepts and skills that are usually considered essential, defining features of "engineering." Although it is impossible to separate concepts from skills in engineering practice, the research literature tends to treat them separately. Thus, for the sake of simplicity, this chapter follows that dual structure.

The discussion of each skill or concept addresses (1) difficulties encountered by K–12 students in learning that particular concept or skill; (2) the development of students' understanding and cognitive capabilities during their K–12 years; and (3) the experiences and teaching interventions that facilitate an increasingly sophisticated understanding of each concept or skill. Based on the these three issues, the committee identified common principles: (1) the allocation of sufficient classroom time; (2) student engagement in iterative design activities; (3) sequencing of instruction that moves from easier-to-learn concepts to more difficult-to-learn concepts; and (4) the integration of tools (e.g., computer software or computational devices). These principles are discussed in more detail at the end of the chapter.

ENGINEERING CONCEPTS

Engineers generally agree that the prototypical engineering process is design and redesign. However, engineering design is not the same as trial-and-error "gadgeteering." Engineering design involves the following essential components: identifying the problem; specifying requirements of the solution; decomposing the system; generating a solution; testing the solution; sketching and visualizing the solution; modeling and analyzing the solution; evaluating alternative solutions, as necessary; and optimizing the final design. These essential components can be categorized into three type-specific groups of engineering concepts: basic science and math concepts, domain-specific concepts, and concepts common to most areas of engineering. Though this review does not focus on the social aspects of engineering design, engineering design is an inherently social enterprise, since those involved typically are working in teams and must communicate with clients or other stakeholders.

Research on the development of science and math concepts is not discussed in this chapter but has been extensively reviewed in recent studies by the National Research Council (e.g., *Taking Science to School: Learning and Teaching Science in Grades K–8* [Duschl et al., 2007] and *Adding It Up: Helping Children Learn Math* [NRC, 2001]). Very little research has been

TABLE 5-1 Engineering Concepts in the Categories of Systems and Optimization

Systems	Optimization
Structure-behavior-function*	Multiple variables*
Emergent properties*	Trade-offs*
Control/feedback	Requirements
Processes	Resources
Boundaries	Physical laws
Subsystems	Social constraints
Interactions	Cultural norms
	Side effects

*Related empirical research on K–12 students is available on these concepts.

published about the development of domain-specific concepts, some of them closely connected to particular engineering disciplines (e.g., statics), in K–12 students. In fact, with the exception of students who enroll in higher level math and physics courses in high school, very few K–12 students are even exposed to these concepts. Based on Silk and Schunn's (2008) review of relevant literature, which includes national and international content standards in technology education and engineering, the concepts that are common to most areas of engineering include structure-behavior-function (SBF); trade-offs, constraints; optimization; and system, subsystem, and control. The discussion of the concepts is divided into two categories: systems and optimization. As depicted in Table 5-1, the majority of empirical research on systems focuses on the concepts of SBF and emergent properties (i.e., behaviors that emerge from dynamic interactions among system components). Most of the research on optimization is on multiple variables and trade-offs.

Systems

The concept of a system relates to how individual components of an object or process work together to perform a function. The analysis and design of systems is central to engineering, the purpose of which is to modify surroundings to achieve particular purposes. Engineers may focus on the role and performance of individual parts, subsystems, or levels in a system, or they may highlight the boundaries and interactions between a system and its surrounding environment. Thus the concept of a system has many aspects

and can serve different purposes in the engineering design process. Thinking in terms of systems involves understanding (1) how individual parts function, (2) how parts relate to each other, and (3) how parts, or combinations of parts, contribute to the function of the system as a whole.

Structure-Behavior-Function

SBF, a framework for representing a system, can be used to describe both natural and designed systems. SBF relates the components (structures) in a system to their purpose (function) in the system and the mechanisms that enable them to perform their functions (behavior). The SBF framework has been used to explain designed physical systems, such as electrical devices (Goel, 1991; Goel and Bhatta, 2004), as well as to represent the process of design as conducted by experienced designers (Gero and Kannengiesser, 2004). Empirical evidence (Gero and Kannengiesser, 2004) suggests that functional considerations actually drive the design process for more experienced designers, who often label the framework FBS to reflect the change in emphasis. For our purposes, we distinguish between the three aspects of design without formally choosing their order of importance.

Researchers have found that young children, and even preverbal infants, seem to have a strong sense of cause-and-effect principles (Bullock et al., 1982; Koslowski, 1996; Leslie, 1984). By the end of the preschool years, most children can use reasoning processes and problem-solving strategies, including evaluating simple if-then rules. Thus they already have developed many capacities when they enter the formal learning environment (Duschl et al., 2007).

Based on a review of the literature, however, the commissioned authors concluded that very young students (second graders) are unlikely to spontaneously consider what causes an effect, the basis for an SBF understanding of a system. Older students (fifth graders) are more likely to consider the cause, but, in general, younger students are much more likely to consider surface features, even when prompted to think about what affected the system under investigation (Silk and Schunn, 2008). Younger students often use a device for its functional purpose without inspecting the elements or components of which the device is made (Rozenblit and Keil, 2002).

For example, Lehrer and Schauble (1998) interviewed second- and fifth-grade students to assess their reasoning about the mechanics of gears. The students were shown increasingly complex combinations of gears on a gearboard that performed no function and gears in familiar machines with

a known purpose (e.g., a handheld eggbeater and a 10-speed bicycle). They found that, even though all aspects of the devices could be directly inspected and had no hidden parts, the students' ideas about the structures in the devices and the mechanisms that made them work varied by grade level.

Fifth graders were more likely than second graders to form causal chains of relationships among three or more components in the functional devices. In the function-free context, they were more likely to identify the gear teeth as the important feature that drives the motion of the gears. Interestingly, in the functional context (i.e., the eggbeater), both groups were likely to mention the gear teeth. In this case, the improved performance of the second graders may indicate the importance of context in helping young students to reason about causal mechanisms.

When fifth and sixth graders were compared, students at both grade levels were equally likely to mention that the relative gear size determined the speed of the gears, but sixth graders were more likely to take that idea a step further and actually count and calculate the ratio of gear teeth to velocity. Fifth graders also used this mathematical reasoning when analyzing more complicated combinations of gears, which may have been their way of minimizing the complexity of the task.

The authors of the study caution that, even when the structures of a design are visible, young students may recognize the function of an object without considering how the underlying structures contribute to the performance of that function. In addition, early elementary students appear to lack sophisticated strategies for explicitly articulating causal mechanisms and for using mathematical representations as tools to represent complex causal behaviors. However, when children are provided explicit support for developing mathematical descriptions of natural systems, they can often use them to support their understanding of causal mechanisms (Lehrer et al., 2001).

Studies by Hemlo-Silver and colleagues on differences between adults and students focused on how the understanding of systems in terms of SBF changes over time and with experience (Hmelo-Silver and Pfeffer, 2004; Hmelo-Silver et al., 2004). They found minimal differences between the way pre-service teachers and sixth graders think about structures. However, they found large differences in how they understood functions, and even larger differences in how they understood causal behaviors, which require an appreciation of "connectedness" among elements in a system. The authors suggest that causal behaviors are the most difficult to understand, because they are often dynamic and invisible, whereas functions lead to specific outcomes that are visible.

Silk and Schunn (2008) found that research on elementary and middle-school students (Kolodner et al., 2003; Penner et al., 1997, 1998) suggests that a primary method of advancing students' ideas about SBF was to engage them in designing models, especially successively complex models. Students' first models tend to focus on superficial features and structural features. However, as models are revised and refined, many constructive ideas come into play. In addition, teacher support appears to have a large impact on whether, and how much, model building furthers an understanding of the SBF concept. Teachers' questions that focus attention on design help students set step-wise, pragmatic goals for each revision, which deepens their understanding of SBF.

With considerable teacher support, both early elementary students and middle school students can move toward a conceptual understanding that emphasizes function, just as experienced designers do (Penner et al., 1998). Effective teacher strategies include (1) pointing out limitations of the class models as a whole (e.g., if none of the initial models includes a mechanism for motion, the teacher may suggest that students consider the specific idea of motion in their revisions); (2) providing information when there is no way for students to discover the information on their own (e.g., providing the mathematical concept of median as a way of representing a range of data); and (3) encouraging individual teams of students to pursue specific design challenges that extend their models in general ways (e.g., considering how the function of the object under investigation is similar to and different from a familiar related object). Students whose teachers used these strategies were able to design increasingly complex functional models, including models of the mechanism of motion, and then to develop data representations to support their claims about the performance of their designs.

The importance of teacher input cannot be overemphasized. Unfortunately, teachers who have had little or no experience with formal modeling may not have a deep understanding of the process and thus may not be able to formulate questions to guide students engaged in exploring functional relationships among constituent parts of models. Teachers who have not participated in differentiated, sustained staff development, may also lack underlying training in science and, therefore, may not be able to explain basic natural phenomena.

Another factor that can negatively affect students' conceptual understanding of SFB is the amount of time allocated for design/redesign cycles. In an already crowded curriculum, it may be difficult to set aside enough time for modeling activities that are not merely superficial exercises. So,

although the findings about younger students' abilities to develop modeling concepts are encouraging, effective teacher development and making room in a crowded curriculum are paramount concerns.

Emergent Properties

Not all systems can be analyzed in terms of causal behaviors or a direct, linear sequence of events. Another framework for understanding systems is focusing on behaviors that emerge from dynamic interactions among system components. These emergent properties can be global, aggregate, or macro-level behaviors that emerge from local, simple, or micro-level interactions between (or among) individual elements or components of a system. Aggregate behavior is qualitatively distinct from the sum of behaviors of individual components and indicates a complex engineered system, such as highways, the Internet, the power grid, and many others, which are all around us.

Based on their review of the literature, Silk and Schunn (2008) concluded that a major impediment to understanding the concept of emergent properties is the strong, perhaps innate, tendency of individuals to ascribe a central plan or single cause to system behavior (Resnick, 1996). Thus, analyzing emergent properties, which requires thinking on multiple levels of a system, may be particularly difficult for elementary-age students. However, there is not enough research to support that claim, because most of the empirical studies on emergent properties have been with students in middle-school or above. It is possible, however, that the concept of emergent properties is not understood through everyday experiences, even by adults (Resnick, 1996), and may require special support or learning experiences.

In Resnick's study, 12 high school students used StarLogo, a complex systems-modeling program created by Resnick based on the Logo program, in which users specify the behaviors of individuals, then observe how interactions among them give rise to group-level behaviors. Working mostly in pairs, and with considerable help from Resnick, the students developed individualized projects using StarLogo.

For example, one project was a model of traffic flow on a one-lane highway. The behavior of each car was governed by three basic rules: (1) if a car was close ahead, the trailing car slowed down; (2) if no cars were close ahead, the car speeded up until it was going the speed limit; and (3) if a radar trap was detected, the car slowed down.

When traffic jams developed, the students first reasoned that the slowdowns must have been caused by a specific, localizable event or circumstance,

which they decided was a speed trap. When they removed the speed trap, effectively eliminating rule 3, they were surprised that traffic jams continued to develop—even if all of the cars started at the same speed. Only when they specified that the cars move at a uniform speed and start from equally spaced positions, did each car accelerate to the speed limit and continue moving at that speed, thus ensuring the smooth flow of traffic.

Thus the randomness of the initial spacing of cars led to the emergent behavior—traffic jams. This result was directly counter to the students' ideas, which Resnick characterized as a *centralized mindset*. Their initial reaction was to assume that a "leader" (e.g., a bird at the head of a flock) or a specific restriction (e.g., a speed trap) was the reason for the emergent behavior.

As Resnick's concept of a centralized mindset suggests, most of the students, in fact most adults, prefer explanations based on a central control, single cause, and predictability. However, as the students tested their simulations with different starting parameters and refined their rules, and as Resnick continued to challenge their assumptions, they began to appreciate decentralized thinking and the concept of emergent properties. Levy and Wilensky (2008) found that in coping with emergent properties, middle school students often negotiated the relation between individual and aggregate levels by inventing an intermediate level involving a collection of individuals. The intermediate level facilitated understanding, because students could still identify individuals while simultaneously viewing how individual interactions produced aggregate behaviors that were not identical to those of the participating individuals. Taken together, these data suggest that once a person understands emergent properties, he or she can begin to reason about decentralized control and multiple causes and, eventually, understand stochastic and equilibration processes.

Resnick's conclusion that, with proper guidance, students can recognize emergent properties is supported by evidence from two studies by Penner (2000, 2001). The goal of these studies was not simply to characterize students' (sixth graders) understanding of emergent properties, but also to investigate ways of supporting the development of their understanding. Penner showed that through simulation, sixth graders were able to consider the idea that macro-level order in a group did not require an explicit, central plan. They learned that order may emerge when individuals follow simple rules in their interactions with each other.

An important precondition for the success of the simulations was proper motivation. The students understood how the simulation was related to the

real-world question they were studying in their classroom, and they clearly predicted the results of the simulation.

Besides a centralized mindset, students may also naturally try to understand emergent behavior in terms of what they already know, such as direct causes or material substances. In a series of studies, Chi and her colleagues proposed that some misconceptions about scientific phenomena are difficult to change because they are classified conceptually in an inappropriate ontological category (Chi, 2005; Chi and Roscoe, 2002; Reiner et al., 2000; Slotta and Chi, 2006; Slotta et al., 1995). For example, as children become aware that plants are alive, they tend to overgeneralize the characteristics they associate with living things. Most children believe that plants "eat" or absorb nutrients through their roots, rather than synthesizing sugars in their leaves (Roth, 1984).

In short, these studies suggest that students must first be helped to form a category of emergent properties and then encouraged to restructure their existing understanding to align with their new understanding of emergent properties.

After reviewing the literature on cognitive reasoning, Silk and Schunn concluded that simulations in the classroom context can clarify connections between different levels of a system and help students transition from a strong tendency to attribute behaviors to central plans and/or single causes to a perspective more consistent with the concept of emergent properties. Investigations of how simulations influence the teaching of emergent properties include studies of the effects of life-sized, participatory simulations (e.g., Colella, 2000; Penner, 2001; Resnick and Wilensky, 1998) as well as software environments that help students manipulate complex systems (Resnick, 1996; Wilensky and Reisman, 2006; Wilensky and Resnick, 1999).

Although research indicates that both types of simulations were helpful, software environments tended to be more effective because students could more easily explore, manipulate, and finally understand concepts that spanned levels of a system (Resnick, 1996). Evidence also indicates that making connections between levels of a system explicitly facilitates students' understanding of emergent properties and that dynamic simulations make connections between the levels of a system apparent and thus easier to identify and understand (Frederiksen et al., 1999).

Optimization

The concept of optimization in engineering relates to the stage of the design process in which the functionality or effectiveness of the design is

maximized (ITEA, 2000). Real-world designs must always meet multiple, conflicting requirements and are always subject to constraints. Thus optimization necessarily involves trade-offs among different aspects of a design to improve one quality at the expense of another (e.g., range of motion versus mechanical advantage or additional strength versus added material cost). The requirements and constraints may include (1) available resources, (2) cultural and social norms that influence how the qualities of a design are valued, and (3) physical laws that determine how things work. Thus, optimization is a core concept that brings together many related engineering concepts, including trade-offs, requirements, resources, physical laws, social constraints, cultural norms, and side effects.

None of the literature on cognitive development or the learning of science directly addresses the difficulties for K–12 students in understanding the concept of optimization in the context of engineering. Therefore, this discussion is focused on concepts that are relevant to the idea of optimization, although they may be discussed in slightly different terms. For instance, optimization can be thought of as the manipulation of the internal variables of a system or product to maximize the external performance measures of that system or product.

Understanding conceptually how to simultaneously consider the effect of multiple variables on an outcome is essential to optimization. In addition, when variables interact, trade-offs must be considered. Thus making trade-offs is an essential concept in student's understanding of optimization in engineering.

Multiple Variables

The goal of engineering is to design products or processes that result in predictable outcomes within a given set of resource and other constraints. Almost all real-world products or processes are designed based on trade-offs among a large number and wide range of input variables that have been "manipulated" to reach an optimal solution. That manipulation must be based on knowing which variables have a causal effect on the outcome.

People with an interest in introducing engineering concepts to young children may be concerned that children are simply not cognitively ready to work on complex engineering problems that require taking into account many variables and requirements. Overall, cognitive processes gradually improve throughout childhood. These include processing speed, working memory, and executive functioning (Kail, 2004). These general, age-

dependent aspects of cognitive functioning can have a significant influence on task performance. However, domain-specific aspects (e.g., task strategies and prior knowledge) are as important, if not more so, in children's learning. Furthermore, considerable evidence supports cognitive load theory (CLT), which argues that the seemingly infinite intellectual capacity of humans is primarily attributable to modifications in long-term memory; short-term memory, at all ages, is tightly constrained to consideration of a maximum of five to seven elements at a time (Sweller and Chandler, 1994). Even well-practiced adults can only process three or four variables simultaneously without compensating for their constraints by some sort of "chunking" or bundling strategy or linear processing (Halford et al., 2005). So, although students' capabilities almost certainly do improve over the course of their years in K–12, many aspects of real-world engineering design are beyond the cognitive processing limitations even of adults.

Based on their review of the literature, Silk and Schunn came to the same conclusion—that the large number of variables involved in most engineering contexts can easily overwhelm the limited cognitive resources of most individuals, adults or students (Halford et al., 2005; Kuhn, 2007; Kuhn et al., 2000; Schauble et al., 1991). They also found that meta-level knowledge about the nature of causality and the goal of testing can organize their thinking about design. In addition, simplifying tasks by focusing on subproblems and using external representations (physical and mathematical) are effective strategies that can be taught to students in the K–12 setting. In fact, they found that a number of strategies can help young students overcome memory constraints and lead to mature learning, as well as authentic engineering practice. Research shows that these strategies can be learned in classroom settings.

For example, one strategy is to help students build schemas for analyzing multivariable systems, such as the strategy of assuming additive and consistent effects while controlling independent variables. Although these concepts can be explained at the meta-level, evidence suggests that they can be taught to young children by explicit instruction or experimentation (Keselman, 2003).

"Chunking" is another strategy for overcoming memory constraints. Similar to context-specific schemas, chunking involves creating a mental representation of a situation as a discrete element in memory with many aspects hidden underneath it (Chase and Simon, 1973; Miller, 1956). Another strategy—functional decomposition—is a design-specific strategy that can also be used to simplify a system and focus on one part of it. For example,

the Wright Brothers used functional decomposition to isolate the effects of different aspects of the plane for testing before they built the entire system (Bradshaw, 1992). A third strategy is to produce physical representations of ideas to help students understand complicated situations. For example, a representation might be in the form of a prototype of the design that makes most aspects of it concrete and visible (Bradshaw, 1992).

Other strategies include "mathematizing," taking notes, and sketching. In mathematizing, conceptual ideas are represented as mathematical relationships. In contrast to prototyping, mathematizing purposely makes only some variables concrete and hides others. Studies by Lehrer and colleagues (2000) have shown a relationship between conceptual change and mathematizing. Note taking (Garcia-Mila and Andersen, 2007) and sketching (Anning, 1997; MacDonald and Gustafson, 2004; MacDonald et al., 2007) can also facilitate learning when working with multivariable systems. Sketching is more abstract than prototyping, more concrete than mathematical or graphic representations, and allows for hiding or deemphasizing irrelevant variables.

In short, Silk and Schunn found that strategies for simplifying tasks by focusing on sub-problems and using external representations (physical and mathematical) are effective learning strategies in the K–12 setting that enable students to construct and evaluate complicated designs in systematic ways.

Trade-offs

Trade-offs are one aspect of all real-world engineering design (Otto and Antonsson, 1991). They are always necessary in optimizing a system, both when considering input variables, which can be manipulated in the design process, and outcome variables, which indicate the quality of the design. A trade-off of an input variable occurs when a modification of the level of that variable impacts the effect of another variable on the outcome of the design. Thus trade-offs are not simply combinations of variables that influence an outcome in an additive way. There can also be cases when variables have opposing impact on an outcome. For example, the goals of controlling costs and producing the most effective product possible are often at odds.

Based on their review of the literature, Silk and Schunn (2008) concluded that, because K–12 students are unlikely to have a normative understanding of interactions among variables in a general sense, they may not easily come to a conceptual understanding of trade-offs. Nevertheless, some research studies (Acredelo et al., 1984; Zohar, 1995) have shown that youngsters may

have some kinds of understanding that can be a basis for a more complete grasp of the trade-off concept.

For example, even in well understood physical settings, younger students understand direct relationships before they understand indirect relationships. Thus when considering the relationships between distance, time, and speed, fifth graders are likely to understand that speed is directly related to distance and that time is directly related to distance, but they are not likely to understand that speed and time are indirectly related to each other (Acredelo et al., 1984). Although it is not clear how students transition toward understanding indirect relationships, which are more cognitively demanding, an understanding of direct relationships in a system may be a necessary precondition.

Despite the difficulties of understanding trade-offs, Silk and Schunn concluded that certain classroom strategies can help students to consider trade-offs. One strategy is (1) to use mathematical representations to make connections between variables explicit and then (2) to engage in successive iterations in which variables are considered in isolation and in then in combinations (Schwartz et al., 2005). Mathematical formulas may be one way of conceptually representing trade-offs and thus helping students to consider variables that are indirectly related.

Schwartz and colleagues (2005) have demonstrated the effectiveness of simply encouraging students to represent situations mathematically. In a series of three studies, the first two with fifth graders and the third with fourth graders, they presented students with a balance-scale task (Siegler, 1976) in which they were asked to consider forces over a distance by predicting the outcome of balances that varied in two dimensions—the number of weights on each side and their distance from the fulcrum.

In the first study, they represented the weights as discrete pegs and as beakers of water filled up to different levels. The students in the beaker scenario were more likely to reason only about weight and not to consider the effect of distance. The researchers concluded that these students were less likely to quantify the beakers into discrete values, which made it more difficult to consider both dimensions simultaneously.

In the second study they tested this hypothesis. Students were given only peg problems and then asked to justify their predictions. Some students, however, were asked with a general prompt ("explain you answer"); others were asked to use math ("show your math"). Only 19 percent of the first group ("explain") considered both dimensions in at least one problem; in the second group ("math"), 68 percent considered both dimensions in at

least one problem. Students in the first group switched between distance and weight as a justification, especially after receiving feedback on a problem they had predicted incorrectly, but they did not often represent the dimensions simultaneously.

Students in the second group also did better on more complex problems with weights at multiple locations on each side of the scale. Among all students who did consider both dimensions, the students in the second group were also more likely to consider both dimensions on these more challenging transfer problems.

The third study was similar to the second, but no sample justifications or examples of how to count were provided. The students, fourth graders, were less likely to use the multiplicative rule when predicting outcomes. However, the students in the math group did better on more complex problems with weights at multiple locations on each side of the scale; that is, they were more likely to use both dimensions in predicting outcomes.

Schwartz et al. considered these results in the context of extensive developmental research on the balance-scale task (Siegler, 1981), which showed that the reasoning of fifth graders was similar to that of kindergartners when they were presented with a problem that included hard-to-measure, continuous quantities in the form of a beaker. However, these same students performed as well as their peers when the problem included discrete, easy-to-quantify pegs. When they were given explicit instructions, feedback on their predictions, and encouragement to justify their answers mathematically, their reasoning was on a level similar to that of adults. Thus these studies provide compelling evidence that students, when encouraged to use mathematics, can represent physical situations and reason about them, even if they involve variables that are related indirectly.

The results of the studies described above have been supported by subsequent research with younger children. For example, in a study by Lehrer et al. (2000), second graders who were asked to reason about speed and distance were influenced by attempts to create mathematical models of the slope of the ramps they were using to study the movement of cars. In this case, the mathematical models were provided to one group of students, while another group had to invent the mathematical models themselves. The exercise only had positive effects for the second group.

Working on complex mathematical problems requires that students consider multiple paths and options in attempting to design optimal solutions. In another study, high-achieving sixth graders and college undergraduates were asked to develop individual business plans for a dunking booth at a

school fair (Vye et al., 1997) using mathematical problem solving. To find possible solutions, college undergraduates were much more likely to consider more than one plan and select among them. But neither group was likely to test their solution against all of the initial constraints.

In a follow-up study, pairs of fifth graders were just as likely as the undergraduates to consider multiple solutions and to consider one or both of the constraints on their expenses. Success in this study was predicated not on the number of goals generated by each pair of students, but by appropriate reasoning and sound execution of the goals. Students who engaged in explanatory reasoning and counterarguments searched more of the "solution space" by monitoring each other, thus increasing their successful problem solving. This study provides some evidence that young students are capable of considering very complex mathematical problems that involve searching for optimal solutions. And, in this case at least, students seemed to benefit from having a partner who challenged them to justify their ideas and to monitor their subsequent actions.

ENGINEERING SKILLS

To understand the engineering process, K–12 students must learn not only engineering concepts, but also necessary skills. In their integrative review of research results on the development of core engineering skills in K–12, the commissioned authors focused on skills related to design and redesign, which are the prototypical engineering processes (Petrosino et al., 2008). The necessary skills include defining the problem, specifying requirements, decomposing systems, generating solutions, drawing and creating representations, and experimenting and testing. Because empirical evidence about how students develop most of these skills is limited, the commissioned authors could only glean evidence on the latter two topics, the development of drawing and representational skills and experimentation and testing skills.

Drawing and Representing

In professional design practice, drawing and representing have several purposes. Doodling commonly facilitates nascent ideas. "Exploded views" not only reveal the assembly of complex devices and their components, but also suggest the functionality of the system and components. Side and top schematics and computer-aided design (CAD) renderings show the

aesthetics and scale of a device. Finally, drawings can communicate ideas and constraints (Anning, 1997; King and Fries, 2003; Stacey and Lauche, 2004).

Other forms of representation, such as modeling and "making" are also used in design. Various aspects of making representations are considered part of the design process, as it moves from concept to embodied design. Designers also use gestures and objects in their representations (e.g, they use their bodies to understand and convey their designs, especially inchoate designs). In the discussion that follows, the word "making" is used in relation to incipient design ideas.

From their review of the literature, Petrosino and colleagues (2008) concluded that, for children, drawing tends to be a way of recording significant personal events (Anning, 1997). Unless there is deliberate intervention, children's drawings are unlikely be used for design.

For example, drawing as part of a design activity has been described in an ethnographic study of design implementation for early elementary students in Australia in which students designed, made, and appraised vehicles (Rogers, 2000). After lectures on wheels, young students were shown examples of vehicles and instructed to make, out of simple objects, a vehicle with at least one wheel and then to draw it. The students were then divided into pairs, and each pair was asked to draw a picture of a vehicle to make and then to make it; they received no guidance on either of these steps. The student pairs did not directly compare their vehicles, although the teacher provided some comments.

This example highlights a number of missed opportunities and pitfalls. First, the teacher did not explain the differences between a design drawing and other types of drawings, and the students obviously did not understand the difference. This was apparent from the drawings themselves, which included details such as people and roads that were not related to the task at hand, and in the absence of details regarding the materials the vehicle would be made from. Also, conversations among students while drawing their vehicles did not focus on details such as what the car should be built from.

Second, because of the lack of connection between the design (drawing) phase and the making-and-appraising phase, students understood design as a linear, rather than iterative process, in which drawing served little or no purpose. In fact, the drawings had little correlation to the vehicles the students made (Rogers, 2000).

Third, although not noted by Rogers, Petrosino et al. suggested that the teacher could have drawn students' attention to the connection between design and the constructed vehicles by showing examples of vehicles before

asking them to make drawings. Similar results in studies of elementary students also showed a lack of innate connection between a drawing and design (Anning, 1994; Samuel, 1991; Williams, 2000). In addition, young students have difficulty creating design drawings, which involve "graphical conventions of representing scale, spatial orientation and overlap" that are unfamiliar to them (Anning, 1994).

Other kinds of representation, such as models, without intervention, may preserve only structural and superficial features. Penner et al. (1997) conducted a study in which lower level elementary school students were asked to design functional models of elbows. Prior to the modeling activity, when students discussed the purpose of a model, the recurring criteria was physical resemblance. However, after a discussion of how models differ from real things, the students began to understand the functional differences between a simple, representational drawing and a model. The children, who worked in pairs, had access to a variety of everyday materials to make their models.

At first, the children tended to see models as small, superficial copies of the thing itself. Initially, the models were copies of the form of an elbow, but they did not perform the functions of an elbow. Although some of the models could flex, the flexure was unrestrained in direction. Discussion with the children revealed that they did not isolate the motion of the elbow and that they inferred a greater range of motion based on the pivot of the shoulder. After experimenting with real elbow movements, the students made new models. This time, the models incorporated constraints but also included more nonfunctional, but physically similar, details, such as representations of veins.

Johnsey (1995) conducted a study of pre-K through fifth-grade students in the United Kingdom to investigate the role of making in design. Eight case studies of students who tried to create designs with little or no teacher intervention revealed how children think about representations. Johnsey found that making representations played a role early in the design process; that it supported other design process skills, such as clarifying, specifying, and researching; and that it occurred in tandem with planning, generating, and modeling. The activity could generally be considered a make-evaluate-make cycle.

Making also encourages the development of a common design language among children. When students begin building well before they finalize their design (a divergence from professional design), they gain experience in moving between the actual and the possible. They develop norms and vocabulary

appropriate to their designs as they need them, rather than imposing them from the beginning of the activity (Roth, 2001). Representations are particularly effective in collaborative situations (Arias et al., 2000). One of the benefits of design activities is that thinking and acting become inextricably connected. In fact, with continued iterations, designs become "tools to think with" (Roth, 1996).

The reviews of the literature by the commissioned authors show that, although schoolchildren do not naturally use drawings and representations effectively in the design process, some classroom practices can have a positive impact on the way they use them. Allowing young children to play with the construction materials they will use can lead to better design drawings, particularly when children also participate in a discussion of how their drawings will be used. Comparing drawings done before and after design can help determine the usefulness of the initial drawing (Claire, 1991; Pace and Larson, 1992).

Drawing and representing are useful methods of eliciting nascent ideas, but design representations tend to be highly specific and do not easily lead to abstraction or transference to other situations (Gick and Holyoak, 1980). Nevertheless, repeated experiences related to a single complex concept can encourage abstraction, and students' representations do evolve and improve over the course of the dynamic design process (Spiro et al., 1991). Iterations of a full design cycle can improve learning and challenge students to "translate experiential knowledge into abstract rational form" (Hill and Smith, 1998).

For young children, a preliminary to drawing may be investigation and exploration of materials. In one study, lower elementary students were allowed to play with a limited selection of materials and explore their possibilities before being asked to draw and then make a figure from those materials (Samuel, 1991). To support their drawings, they were supplied with notes about the materials and instructions, such as drawing top and side views rather than perspective views.

Another study (Fleer, 1999) in which children who were asked to draw designs of forts they had constructed led to an interesting observation about plan-view versus side-view drawings. The point of view tended to correlate with the drawing position of the child. If the fort was on the desk, the drawing tended to be a side view; it the model was on the floor, the drawing tended to be a plan view.

For young students who may not know what engineering is, contextualizing their design activity by using simple, familiar objects can be productive.

Solomon and Hall (1996) explain that drawing ability may be accelerated when students learn the various roles a drawing may play. Craft skills improve with familiarization via direct experience with the tools and materials to be used. Improvement in craft skills leads to improvement in spatial ability, including visual and haptic shape recognition, as well as manipulation and translation between two and three dimensions (Solomon and Hall, 1996).

In their review, Lehrer and Schauble (2006) pointed out various methods of instruction that evidence shows support modeling. First, informed decisions about the sequencing and timing of introducing new and more difficult forms of modeling are critical to support student learning. Second, involving students in group activities is essential to helping students understand and appropriate the inquiry processes, emphasize the development and use of different forms of representation, and capitalize on the cyclical nature of modeling. Third, modeling approaches only develop when inquiry is a priority in the classroom. Fourth, nuanced forms of modeling require a long-term effort and are more likely to develop in students who build on successively complex experiences with modeling. Finally, although this is not usually done in traditional classrooms, critiquing and discussing their own models and those of other students can support students' understanding of engineering design.

Experimenting and Testing

In professional practice, engineering designers use experimentation and testing to determine the level of optimization of a design and whether all of the requirements have been met. This step may be done with full or partial prototypes or with virtual models using finite elements analysis. Unlike scientific experimentation, the purpose of which is to identify causal relationships through a process that does not involve optimization and trade-offs, engineering experimentation and testing are iterative processes with multiple steps, including modeling and analysis (Schauble et al., 1991). The differences can be attributed to the similar but different purposes of engineering and science.

As described in Chapter 2, scientists ask questions about the world around us, whereas engineers modify the world to adapt it to our needs. Scientific inquiry is concerned with what is, while engineering design is focused on what can be. Models may be used by both, but the nature and purpose of models in science and engineering are different due to differences between scientific inquiry and engineering design. Understanding these differences is critical to understanding potential learning outcomes when engineering

is used to teach science, especially because children's engagement in engineering experimentation is done, necessarily, without modeling, analysis, or mathematical optimization, which engineers use with experimentation.

In their review of the literature, the commissioned authors explained that inquiry commonly involves experimentation with multiple variables (Petrosino et al., 2008). However, when middle school students are presented with an activity in which they manipulate variables that contribute to flooding, for example, they tend to focus on outcomes and do not immediately experiment in an analytical way (Kuhn et al., 2000). Rather than isolating variables, they tend to change many at once and attribute the good or bad outcome to *all* variables, even those that had been determined to be good in prior experiments. Although many students progress toward altering one variable at a time, many others consistently alter multiple variables. Kuhn et al. suggest that students with "additive mental models of causality" are able to transition to a multivariate model, while those with "co-occurrence models of causality" are resistant this transition.

To address this issue, students in Kuhn's experimental group were presented with a scenario in which they argued about the effect of one variable. All of the students had participated in the flood activity described above, but more students in the experimenting group made valid inferences. An analysis of a meta-level test demonstrated that the experimenting students developed both implicit and explicit understanding, whereas the larger, control group developed only an implicit understanding and could not justify their responses (Kuhn et al., 2000). This study highlights the importance of attending to a student's experimental strategies.

Experimentation has been posited as a critical prerequisite to learning in design, including posing and solving problems (Childress and Rhodes, 2008; ITEA, 2000). In a study on the effects of experimentation on problem solving, fifth and sixth graders completed two experimentation tasks (Schauble et al., 1991). The first task was to design a canal with optimal water depth for boats traveling at a given speed. This task can be accomplished with no understanding of the causes of buoyancy and still be a complicated problem to solve. Thus although solving this problem requires some characteristic engineering processes, it is more akin to gadgeteering than engineering. The second task was to explore why boats float. This buoyancy task required that students engage in scientific experimentation, including manipulating variables (volume, mass, and position) as they measured the buoyancy using a spring. Although these tasks had some common principles, they required different problem-solving strategies.

Prior to the activities, the students were read a framing statement either about what scientists do or what engineers do to provide a context for their problem solving. After completing the activities, the students were asked to reconstruct what they had learned. Their answers revealed that they approached the two tasks differently, depending on how the task had been framed. When the tasks had been framed as exploring why boats float, students undertook a broader exploration of variables and a more thorough investigation of each variable, even of variables that seemed to be irrelevant to the goal.

The group that completed the water-depth task first showed greater improvement in making valid inferences than the group that completed the buoyancy task first. Despite the framing procedure, the water-depth task led to more inferences based on less evidence, and these inferences were more commonly related to causal variables. The buoyancy task tended to lead to inferences related to both causal and exclusive variables, which are critical to the formation of disconfirming evidence.

This example reveals some of the challenges in using design to teach science. However, the design in the study just described is unlike professional design, in that the design goals are created by the designers themselves, as opposed to being developed by a client or external source (Petrosino et al., 2008). Working within the constrains of the goals provided by a client or external source can have a significant impact on the design process.

Testing is necessary to determine if design requirements have been met. In elementary school classrooms, testing or evaluations are usually done by the teacher, but in professional settings, testing is done by the designer. Teacher evaluations of students' designs can be taken as personal criticism, even when couched as a question, such as "How can this design be improved?" It is recommended, therefore, that teachers evaluate student designs via comparisons to the design drawing, which facilitates metacognition, or via comparison to the original design goals, which is a common practice in professional design and can lead to further optimization. Evaluation also helps to promote the utility of the design drawings (Solomon and Hall, 1996).

Solomon and Hall (1996) suggest that design activities in K–12 classrooms should include a careful description of the customer who commissioned the design. In most studies, the teacher is the customer, which, because of the teacher's power position, can render the evaluation stage challenging and less than fruitful. Children may perform better when designing for themselves, their families, their community, or a historical or fictional character. The last two may also provide opportunities to contextualize design problems

in interdisciplinary ways by tapping into other subjects taught in the classroom. Over-specification, which can cause students to feel less involved in the activity, can also interfere with K–12 design experimentation. Students perform best when the focus is not on any one student's work and when they have an opportunity to negotiate ideas in a group (Solomon and Hall, 1996).

Kolodner's learning-by-design (1997), which builds on case-based reasoning (Schank, 1999; Williams, 1992) and problem-based learning (Barrows, 1986), involves iterations of increasing complexity. In a study of Kolodner's program, Vattam and Kolodner (2006) addressed two challenges in teaching science via design. The first challenge, facilitating students' scientific understanding during design, was addressed by incorporating an explanation tool. In this scaffolding technique, students were prompted to explain the science behind their designs. A focus on the relationships between structures, behaviors, and functions, discussed above, also helped students connect science to design.

The second challenge, coping with time, material, and environmental constraints in the classroom, can be addressed through simulation-based design. The virtual design world enables students to isolate and test their designs before building a prototype in the real world. The ability to test and model at a smaller focal length encourages experimentation that leads to an understanding of the science behind the design (Vattam and Kolodner, 2006).

LESSONS LEARNED

Cognitive development research distinguishes between general developmental constraints (i.e., limitations related to the development of the mind) and knowledge constraints (i.e., limitations based on an individual's experiences and how he/she processes them). Researchers and others disagree about the extent to which these constraints exist, and, if they exist at all, which limitations have a greater impact in different domains of learning (Kuhn, 1997; Metz, 1995, 1997). Regardless of the reasons for cognitive development (architecture or experience), the demonstrated success of a number of the interventions reviewed here, even with students in early elementary grades, clearly shows that certain experiences can support relatively sophisticated understanding of engineering concepts and development of engineering skills.

As this chapter makes clear, there are significant gaps in our understanding of how K–12 students learn and might best be taught engineering

concepts and skills. At the same time, the research that has been conducted provides some important clues about effective approaches to curriculum development and classroom practice. Based on the reviews of the literature in this chapter, we suggest the following guidelines for the incorporation of core engineering concepts (systems and optimization) and skills (representation and experimentation) in K–12 education:

1. allocating sufficient classroom time for students to develop core concepts through immersion in extended design activities;
2. encouraging iterative, purposeful revisions of student designs; and
3. sequencing instruction to build from the easiest-to-learn aspects of core concepts to the more difficult-to-learn aspects.

Sufficient Classroom Time for Extended Design Activities

In every successful intervention we reviewed, significant learning resulted only after an extended time for design activities in a meaningful context. Core engineering ideas and skills cannot be developed in a single class period. These ideas and skills must be developed and elaborated through extended investigations that give students time to engage in the full engineering process of design and redesign. Studies show that design activities are an appropriate context for introducing these core ideas and skills because they retain students' interest and invite increasingly sophisticated ways of understanding.

Iterative, Purposeful Revisions of Designs, Ideas, and Models

The second important idea is that iterative, purposeful modeling appears to be central to helping students to a more sophisticated understanding of the salient idea or skill. Modeling can take the form of a physical design or a conceptual, graphical, mathematical, or diagrammatic design. The models help students answer particular questions based on their analysis of previous designs, and as iterations continue, the questions become increasingly specific and operationally defined, and thus increasingly purposeful. As models are developed, revised, and refined over time, students begin to understand ideas in deeper ways. Ethnographic studies of engineers engaged in design work reveals that modeling is the most prevalent and challenging form of activity (Gainsburg, 2006; Neressian et al., 2003; Nersessian and Patton, in press).

Unfortunately, design in K–12 settings usually allows for only a single iteration of a design, which barely begins to reveal conceptual difficulties and design challenges that require further investigation. For modeling to be used productively in the classroom, mathematics education must allow for the development of spatial visualization and related design skills, and algebraic reasoning.

The teacher's role is crucial in shaping students' questions and directing their revisions. Although it may be tempting to allow students to direct their modeling themselves, the successful interventions reviewed here highlight the importance of the teacher providing explicit guidance and developing activities for investigating and negotiating contested claims. These strategies support students' progress toward increasingly sophisticated understanding and representations. In addition, the iteration of cycles based on the teacher's questioning of students' ideas and suggesting of resources for students to consider is essential to focusing attention on the core idea.

Sequencing Instruction from Easier to More Difficult Ideas

The third important idea is that knowledge builds on itself. Thus a simple understanding of an idea is likely to precede a more complex understanding in predictable ways. This applies to learning both engineering concepts and engineering skills. Although this may seem obvious, the purpose of drawing attention to this principle is to encourage the reader to focus on specifying cognitive developmental trajectories for particular concepts.

Common trajectories in the development of expertise can be identified in any domain of knowledge. Once these are specified, a logical sequence of experiences can be developed to build that knowledge over time. For instance, the commissioned authors found that structure was often easier for students to understand than behaviors or functions. Therefore, beginning an activity at the structural level may provide a basis for moving toward an understanding of the more difficult concepts of behavior and function.

Of course, the learning progressions, types of ideas, and depth of exploration of those ideas must be adapted for different grade levels (Duschl et al., 2007). Unfortunately, the literature on teaching core engineering concepts is not sufficient for us to make specific recommendations at this time. In general, however, our findings indicate that with a well thought out instructional sequence and sufficient time and support students can make the transition from a novice level of conceptual understanding and ability to a more sophisticated level. This is true even for students in the elementary grades.

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